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(NASA-CR-163142) BOOSTER AIRBREATHING ENGINE SELECTION ANALYSIS (General Dynamics/Convair) 20 p

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BOOSTER AIRBREATHING ENGINE SELECTION ANALYSIS (U) WBS Element 3.3.1.4

REPORT NO. 76-549-1-064

June 1971

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June 1971

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FOREWORD

This report documents the results of the booster airbreathing engine selection analysis. It meets the requirements of SSB0006.02-1680. The work was performed in support of Contract NAS9-10960, WBS element 3.3.1.4.

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SUMMARY

The selection of the airbreathing engine for the space shuttle booster is a compromise because of the constraints imposed by mission requirements. The effects of engine weight, bypass ratio, cruise fuel consumption, physical size, and thrust variation with speed, altitude and temperature interact in ways which can lead to different selections for different parts of the mission. The desire for commonality with the orbiter engine selection also exerts an influence on the problem.

The airbreathing engine system for the Phase B baseline booster is sized by the engine-out thrust requirement at the start-of-flyback gross weight with sufficient fuel for return to the launch site, under standard atmospheric conditions, against the 95 percentile Eastern Test Range (ETR) design winds. Desired standard day cruise altitude, with one engine inoperative, is 10,000 feet; since the flyback is always over water, any cruise altitude above sea level (perhaps 1000 feet minimum) is acceptable with two engines inoperative.

The Pratt & Whitney aircraft JTF22A-4 turbofan engine was selected for use in the final Phase B airbreathing engine system (ABES). It has a high thrust-to-weight ratio, is compatible with the selected installation concept, provides acceptable cruise fuel economy, and can be qualified for the shuttle program with reasonable cost and risk. The same engine has been selected for the orbiter so that commonality has been obtained.

The General Electric Company has recently proposed the F101/F12B3 turbofan engine for the shuttle program. The F101/F12B3 has a slightly higher bypass ratio, better cruise SFC, and greater cruise thrust than the baseline engine. However, it is heavier, larger in diameter, and has a higher DDT&E cost to qualify. With further study and design work, it is probable that the F101/F12B3 will become an acceptable alternate engine in the booster ABES.

Both the JTF22A-4 and the F101/F12B3 are proposed derivatives of turbofans currently being developed for military aircraft programs. The military versions of the engines are equipped with afterburners, are designed for supersonic operation, and have a life in excess of 3000 hours. The space shuttle booster application allows removal of the afterburner and its fuel system and requalification of the engine at ratings consistent with a much shorter life (500 to 1000 hours), spent primarily in subsonic, low altitude cruising flight.

SECTION 1

INTRODUCTION

1.1 GENERAL

Selection of an engine for the space shuttle booster airbreathing engine system (ABES) required consideration of many factors. These factors include estimated (or specification) performance, availability, development cost and risk, size and weight, and installation compatibility. Consideration of these factors is discussed in this report.

1.2 REFERENCES

1. Liquid Hydrogen Versus JP Fuel for Booster Airbreathing Engines, Report No. 76-549-1-062.

2. NASA TM Report No. 53872, Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development, 1969 Revision.

3. Airbreathing Engine Installation and Configuration (Booster), Report No. 76-549-1-063.

SECTION 2

AVAILABILITY

The statement of work for space shuttle system definition Phase B specifies a technology base of 1972. This has been interpreted to include all airbreathing engines currently qualified or expected to be in an advanced stage of development by the end of 1972. Major development proposals for engines with a 1972 technology base were ruled out if their funding had not been established in a program other than space shuttle.

The available engines include:

a. Recently qualified military turbofans currently in Air Force or Navy inventory such as the Pratt & Whitney TF30, the General Electric TF39 and the Allison TF41.

b. Commercial engines for the wide-body jet transports: the Pratt & Whitney JT9D in the Boeing 747 and one version of the McDonnell Douglas DC-10, the General Electric CF6 in two versions of the DC-10 and the Rolls Royce RB 211 in the Lockheed L-1011. The JT9D has been in service since January 1970; the CF6 will become operational in the last half of 1971; the RB 211 may be certified in 1972.

c. Military engines currently being developed for funded aircraft programs such as the F401-PW-400 by Pratt & Whitney for the Navy F-14B, the TF34-GE-2 by General Electric for the Navy S-3A and the F101-GE-100 by General Electric for the Air Force B-1. The F100-PW-100 by Pratt & Whitney for the Air Force F-15 uses the same gas generator (or core) engine as the F-401 previously mentioned.

d. Older operational engines, both commercial and military such as the JT3C (J57) turbojet, JT4A (J75) turbojet, CJ805 (J79) turbojet, the JT3D (TF33) turbofan derivative of the J57, the J52 turbojet, and the JT8D turbofan derivative of the J52. (Small turbojets such as the J85 and small turbofans such as the CF700 derivative of the J85 were not considered because of their low rated thrust of less than 5,000 pounds.)

From the "available" engines, only those in categories b and c, above were considered. These types were favored because they use the most recent technology and would require a relatively small investment of development funds for shuttle-qualified models. Among the large commercial turbofans, category b, the General Electric CF6-50C was chosen as representative of the class. All three engines mentioned are in the 40,000 pound (and over) rated thrust class, have bypass ratios over 4.0, have fan inlet diameters greater than 7 feet, and weigh over 7000 pounds each.

Among the military engines, category c, only the F401 and F101 were studied. Non-afterburning derivatives of these turbofans have been proposed by their respective manufacturers for the shuttle ABES application, both booster and orbiter. The TF34 is in the 10,000-pound rated thrust class and is therefore too small for the booster cruise mission (over twenty engines would be required). The F100 is slightly smaller than its companion development turbofan, the F401, so the latter was favored for further study. At the start of the Phase B study, the baseline flyback fuel was specified as liquid hydrogen. In a major trade study, documented in Reference 1, JP was recommended in lieu of hydrogen and this recommendation was accepted by NASA in November 1970. Versions of the leading candidate engines with hydrogen fuel were no longer considered after the adoption of JP for the baseline and are not included in this report.

SECTION 3

PHYSICAL DATA AND RATINGS

3.1 HIGH BYPASS RATIO TURBOFANS

Table 3-1 presents pertinent physical data and ratings on the large high bypass ratio turbofans in use or planned for the latest wide-body jet transports. The selected cruise performance point is representative of booster operation at the start of flyback. The weights and ratings shown are those published by the engine manufacturers for the jet transport application noted. Special versions of these engines with increased thrust ratings and reduced weight are feasible because of the short life and permissive operating environment required in the shuttle program. Data on such special versions has not been furnished by the engine manufacturers.

The cruise specific fuel consumption (SFC) of these engines is significantly better than that obtained with the earlier turbojets and low bypass ratio turbofans. This improvement is attributed primarily to the effect of bypass ratio.

3.2 LOW BYPASS RATIO TURBOFANS

Table 3-2 contains pertinent physical data and ratings on nonaugmented derivatives of the two newest low bypass ratio turbofans. This data is DOD-classified and, in the case of the General Electric Company data, also company proprietary.

The cruise SFC of either of these engines is not as good as the high bypass ratio turbofans (Table 3-1) but the cruise thrust per pound of engine weight is better. In a short range mission, such as booster flyback after entry, the engine weight in the cruise propulsion system is an important factor, as is the cruise fuel requirement.

Table 3-1. Physical Data and Ratings — High Bypass Ratio Turbofan Engines

	JT9D-15 Pratt & Whitney	CF6-50C General Electric	RB 211-22 Rolls-Royce
Applications (s)	747; DC-10 Series 20	DC-10 Series 30	L-1011
Status	Versions in service now in 747	DC-10 Series 10 Flying with CF6-6	To be in service in 1972 (?)
Dry Weight, lb	8370	8175	7278*
Inlet Diameter, in.	93.6	86.5	85.5
Overall Length, in.	128.1	173.0	136.3
S.L. Rated Thrust, lb (std day)	45,500	51,000	40,600
Cruise Data at Maximum Continuous Thrust, M = 0.50, 10,000 ft, Standard Day:			
Thrust, lb	20,996	23,064	21,244
SFC, lb/hr/lb	0.536	0.585	0.543
Bypass Ratio	5.1	4.5	5.0
Cruise Thrust/Weight, lb/lb	2.51	2.82	2.92

*Early specification weight; delivered engines exceed specification

Table 3-2. Physical Data and Ratings — Low Bypass Ratio Turbofan Engines

(Note: General Electric data shown is company proprietary)

	JTF22A-4 Pratt & Whitney	F101/F12B3 General Electric
Parent Military Engine and Application	F401-PW-400 Navy F-14B	F101-GE-100 Air Force B-1
Dry Weight, lb*	2421	2665
Inlet Diameter, in.	37.8	45.5
Overall Length, in. *	130.1	125.0
S.L. Rated Thrust, lb (std day)	18,330	20,230
Cruise Data at Maximum Continuous Thrust, M = 0.50, 10,000 ft, Standard Day:		
Thrust, lb	11,230	11,835
SFC, lb/hr/lb	0.810	0.701
Bypass Ratio	0.75	2.0
Cruise Thrust/Weight, lb/lb	4.65	4.44

*With nozzle

SECTION 4

SYSTEM WEIGHTS

4.1 ASSUMPTIONS

a. The aerodynamic characteristics of the baseline booster configuration, B-9U, are assumed to apply, irrespective of any effects that installation of engines other than the baseline choice might have.

b. Installed engine weight is 30 percent greater than bare engine weight; this is a reasonable approximation in a screening process.

c. JP fuel is used and fuel system weight equals 6.5 percent of the required flyback fuel: fuel system weight includes all tankage, pumps, lines and valves.

d. The cruise distance is 399 nautical miles, performed with one engine failed in standard day atmospheric conditions. The absolute ceiling at the start of cruise weight (with one engine failed) is nominally 10,000 feet.

e. The cruise is performed against headwinds equal to the Eastern Test Range (ETR) 95 percentile design wind velocities, per Reference 2. Figure 4-1 shows the lower portion of this wind profile, in terms of altitude versus speed.

4.2 CALCULATION PROCEDURE

a. Estimate booster B-9U empty weight without engines, fuel system and fuel tank: ≈595,000 pounds.

b. Flyback range required = 399 nautical miles.

c. Booster reference area (A_{REF}), lift-to-drag ratio (L/D), and lift coefficient (C_L) for best specific range: A_{REF} = 8451 ft^2; L/D = 6.0 and C_L = 0.32. The L/D and C_L given are not maximum values but represent approximate levels at which best specific range, or minimum fuel for a given range, is obtained. (Maximum L/D is 6.7 and the C_L at that L/D is 0.45.)

d. For a candidate engine, assume the following:

   1. N = Number of engines installed

   2. W_{FE} = Weight of cruise fuel estimated, lb

e. Begin the iteration by calculating the following:

   1. Weight of installed engines,
      W_{IE} = (N) (Dry Weight/Engine) (1.3), lb

   2. Weight of fuel system,
      W_{FS} = (0.065) (W_{FE}), lb

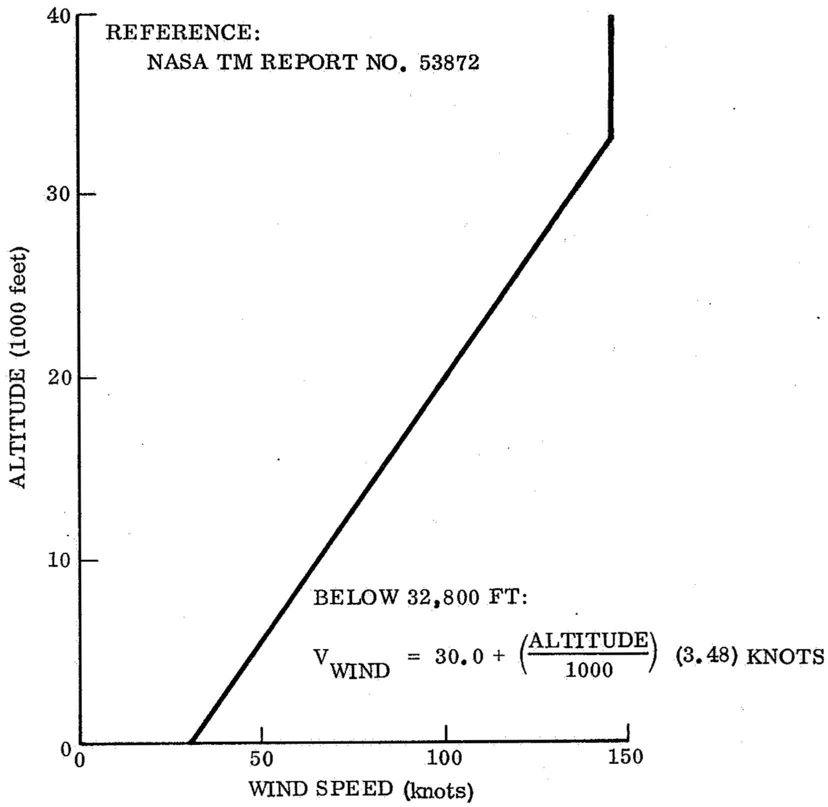

Figure 4-1. ETR 95 Percentile Design Winds

3. Average cruise gross weight,
   $GW_{AVG} = [595,000 + W_{IE} + W_{FS} + (0.5)(W_{FE})]$, lb
4. Required dynamic pressure at GW_{AVG},
   $q = GW_{AVG}/C_L A_{REF} = (GW_{AVG}/2700)$, PSF
5. Thrust required, per engine, with one engine failed, at GW_{AVG},
   $T_R = GW_{AVG}/[(L/D)(N-1)]$, lb

f. Installed performance estimates for the candidate engine are required. These are usually tabulated or plotted as functions of altitude, Mach number and power setting. For a range of altitudes (from 5,000 to 20,000 feet, for example) compute the Mach number equivalent to the required dynamic pressure. For these Mach number/altitude combinations, determine the thrust per engine and SFC at maximum continuous power. Plot these values versus altitude as sketched in Figure 4-2.

g. Enter the thrust curve at the value of T_R (from e.5) and determine average cruise altitude, H_{AVG}. Enter the SFC curve at H_{AVG} and find SFC_{AVG}.

h. At H_{AVG}, calculate the true air speed, V_{TRUE}, from q, the Mach number and the standard day ambient temperature/pressure relationships.

i. Determine V_{WIND} from Figure 4-1.

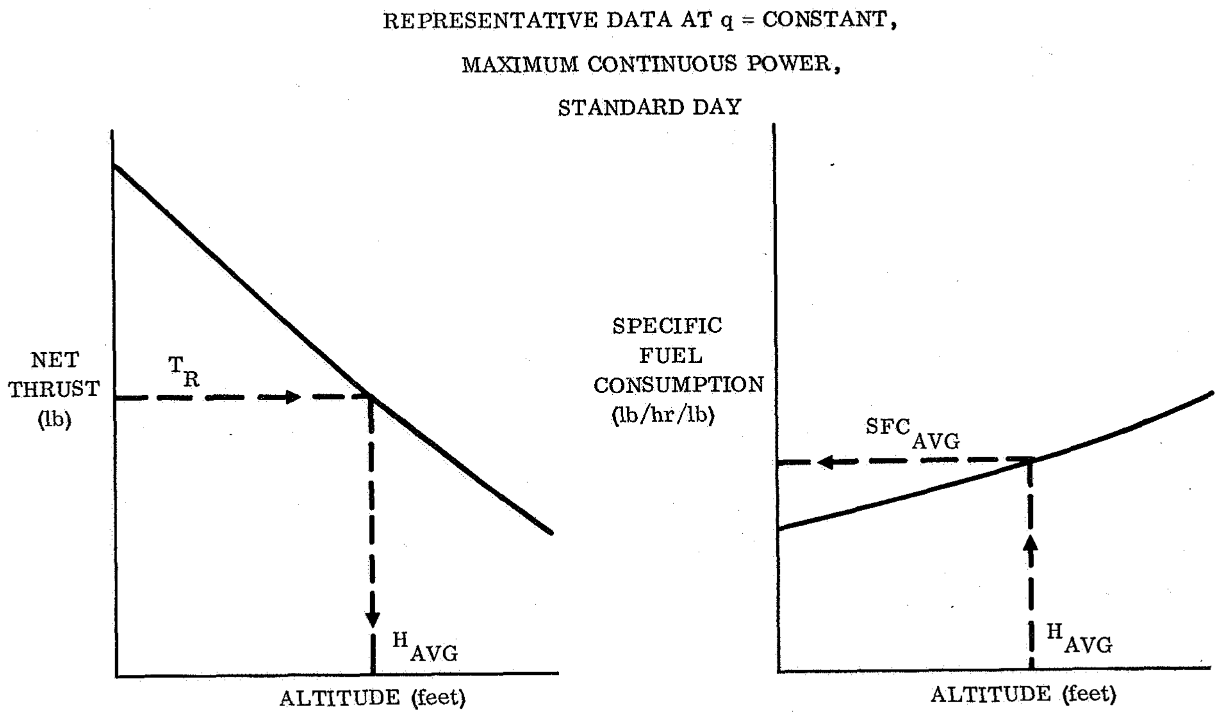

Figure 4-2. Engine Performance Data

j. Determine V_{GROUND}:
$V_{GROUND} = (V_{TRUE} - V_{WIND})$

k. Determine cruise fuel required,
$W_{FR} = (T_R)\ (SFC_{AVG})\ (N-1)\ (RANGE/V_{GROUND})$, lb

l. If fuel required, W_{FR}, is within one percent of fuel estimated, W_{FE}, go on to next step. If required and estimated differ by more than one percent, adjust W_{FE} and repeat process starting at Step e.

m. Determine the start of cruise gross weight,
$GW_{START} = 595,000 + W_{IE} + W_{FS} + W_{FR}$

n. For $(L/D)_{MAX} = 6.7$ and $C_L = 0.45$, determine test values of q and T_R:
$q' = (GW_{START} / [(0.45)\ A_{REF}] = (GW_{START}/3800)$, PSF
$T'_R = GW_{START}/[(6.7)\ (N-1)]$, lb

o. At the Mach number equivalent to the q′ determined in Step n for an altitude of 10,000 feet, verify that the maximum available thrust is equal to or greater than the test value of T'_R calculated in Step n. If this check indicates that an absolute ceiling close to 10,000 feet is obtainable, go to the next step. (If the ceiling is either too low or too high, consideration should be given to adjusting

N and repeating the calculation; this requires judgement based on the trends of prior calculations.)

p. The total system weight is determined:

$$W_{SYSTEM} = W_{IE} + W_{FS} + W_{FR}, \text{ lb}$$

4.3 COMPUTED VALUES

The procedure outlined in Section 4.2 was applied for 3 candidate engines: the CF6-50C, the JTF22A-4 and the F101/F12B3. The results are shown in Table 4-1.

These weight calculations indicate that the B-9U baseline ABES with JTF22A-4 engines is the heaviest of the three systems. However, the effects of engine physical size on booster weight and configuration were not accounted for in this comparison. As indicated in Reference 3, the installation and configuration of the ABES is strongly influenced by the booster configuration. For example, the practicality of installing six CF6-50C high bypass ratio turbofans on the B-9U booster configuration is questionable. The aerodynamic heating problems, discussed in Reference 3, would probably dictate a large but undetermined weight penalty for added high temperature resistant material to protect these large engines.

The comparison of the baseline engine against the F101/F12B3 turbofan is more promising. With this alternate engine the size-related difficulties of a practical installation are not as severe as with the larger CF6-50C. As shown earlier in Table 3-2, the F101 derivative is only slightly larger than the F401 derivative. It should be possible to develop an installation arrangement in B-9U with the F101/F12B3 which would have little (or no) effect on the wing thickness required for internal stowage of the engines. At this point in the study it appears that the ABES weight shown for the F101/F12B3 is probably a bit optimistic. If a thicker wing is required, the minimum impact would be a slight increase in cruise drag. This would increase the required cruise fuel and reduce the indicated 10,850 pound weight advantage. Nevertheless, this comparison indicates that a potential weight saving with the F101 derivative may be realized and further study is warranted.

Table 4-1. ABES Weight Calculations

(Range = 399 n.mi; B-9U Baseline; all Weights in Pounds)

	CF6-50C	JTF22A-4	F101/F12B3
Number of Engines Required, N	6	12	11
Installed Engine Weight, W_{IE}	63,800	35,850	38,100
Required Cruise Fuel, W_{FR}	109,500	143,800	131,500
Fuel System Weight, W_{FS}	7,130	9,350*	8,550
ABES Total Weight	180,430	189,000	178,150
Start of Cruise Gross Weight, GW_{START}	775,430	784,000	773,150
Average Cruise Gross Weight, GW_{AVG}	720,680	712,100	707,400
Average Cruise Altitude, H_{AVG}, ft	8,500	10,500	9,000
Landing Weight	665,930	639,000	641,650

*Weight of forward tank installation (for hypersonic trim) not included

SECTION 5

ENGINE SELECTION

5.1 PHASE B FINAL BASELINE

As discussed earlier, the booster configuration in the Phase B final reports is B-9U. This configuration uses 12 Pratt & Whitney JTF22A-4 turbofan engines derived from the F401-PW-400 augmented turbofan currently being developed for the Navy F-14B aircraft program. Use of the JTF22A-4 in B-9U constitutes an engine selection only insofar as the cruise performance estimates for the booster are predicated on the preliminary weight and performance estimates for the JTF22A-4 engine published by Pratt & Whitney. Since neither the booster nor the engine are currently funded contract end items, further study, proposals, and contract negotiations must be accomplished before a true selection is required.

Considering the status of the "parent" engines from which the leading booster engine candidates would be derived, it is too early to make a firm selection. Neither the F401 nor the F101 will be militarily qualified until 1973. The F401-PW-400 is scheduled to complete a 150-hour military qualification test (MQT) in March 1973 and the F101-GE-100 will complete a 50-hour preliminary flight rating test (PFRT) in October 1973.

It is assumed that a booster/orbiter airbreathing engine competition will be conducted in the near future, on a schedule compatible with the shuttle Phase C and Phase D program milestones. It is further assumed that both General Electric and Pratt & Whitney will propose engines similar to their current study candidates; it is possible that other engines may be offered by these contractors or others not currently active in the Phase B activities.

5.2 GROWTH STATUS OF JTF22A-4

The JTF22A-4 turbofan proposed by Pratt & Whitney represents a minimum modification of the military turbofan. The augmentor and its fuel system components and fuel oil coolers would be removed; a single fixed area convergent nozzle would be installed. The special F14B installation features of the F401-PW-400 would be removed, i.e., inlet stub duct, remote gearbox (with its lube system), power takeoff shaft, and brackets. Space proofing of the lube system and revisions to the engine mounting system would be required. The engine would not be a growth from the military engine in a performance sense. The shorter life required in the booster application allows increased ratings with higher operating temperatures and no turbine material changes.

Pratt & Whitney has issued a budgetary planning estimate of $25 million to qualify (through a 25-hour PFRT and a 50-hour MQT) the JTF22A-4 engine for the shuttle program. The estimate is in 1970 dollars and does not include fuel costs, facility costs, or shuttle vehicle flight test program support. No planning estimates have been issued for shuttle versions of growth derivatives of the military F401, i.e., for engines in the JTF22B family.

5.3 GROWTH STATUS OF F101/F12B3

NOTE

This section contains General Electric proprietary information

The F101/F12B3 turbofan proposed by General Electric involves modifications in the fan rotor assembly while the core or gas generator is essentially unchanged. As with the competitive engine, the augmentor and its associated systems are removed and a single fixed-area convergent nozzle is installed. Space proofing of the lube system and revisions to the mounting system would be required. The performance of the engine represents a significant growth step relative to what would be obtained without the fan modification. An earlier offering by General Electric was the F101/F12A3 which did not involve any fan modification. It had a lower rating, higher weight and, at equal cruise thrust levels, higher SFC. In either engine there were no material or configuration changes in the compressor, combustor, or turbines relative to the military version. Increased ratings and higher operating temperatures are involved with the F101/F12B3, consistent with the short life requirement in the booster application.

Planning estimates of development costs, through space qualification test (SQT), are $59 million for the F101/F12B3 with the new fan assembly. A 42-month program would be required, ending in December 1975. For the lower rated, minimum modification engine, the F101/F12A3, the cost would be $42.4 million through SQT and would require a 37-month program, ending in July 1975. These estimates do not include fuel or facility costs, delivered engines, starters, flight test and operational support. Flight test support, which includes factory and field service engineering, field maintenance, training, and engine spare parts, is estimated at $11.1 million for any F101 derivative for the booster.

5.4 OTHER FACTORS

The published data on the competing engines indicate that the Pratt & Whitney JTF22A-4 was optimized for standard day cruise conditions while the General Electric F101/F12B3 appears to be superior under hot day conditions. All Phase B performance was predicated on standard atmospheric conditions in the flyback portion of the mission. However, in the further development of the booster, it is likely that hotter-than-standard day conditions will be specified. Pratt & Whitney is developing data on rematched versions of the JTF22A to improve its hot day performance. The ultimate engine versions to be offered by the two major manufacturers are expected to be very competitive.

The dry weights given in Table 3-2 are not based on equivalent assumptions. The JTF22A-4 is a minimum modification approach: the weight could be reduced by 185 pounds by material substitutions for non-rotating components and unspecified design changes. The cost of these modifications has not been issued by Pratt & Whitney. The F101/F12B3 weight reflects mainly the changes in the fan rotor and inlet case; the earlier engine, F101/F12A3, was a total of 65 pounds heavier (47 pounds in the fan assembly).

5.5 RECOMMENDATIONS

The JTF22A-4 turbofan is recommended for the final Phase B booster configuration. It is the smallest engine suitable for the mission and is therefore easiest to install. It has a low development cost. The same engine has been baselined for the orbiter and commonality was obtained. Continuing studies of suitable installations of the F101/F12B3 turbofan and follow-on versions of the JTF22 series should be accomplished. The booster ABES should be designed with enough flexibility to accept either of the leading candidate engines or an equivalent, currently unidentified engine.